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14. ABSTRACT The project investigated the use of stochastic models to improve the service performance of distribution centers in the logistics industry. We defined a new metric, called Next Scheduled Departure, which measures the fraction of orders arriving in a 24 hour window that make it onto a target departing truck. The research investigated dynamic worker allocation policies to improve performance on this metric. The results have been recorded in several academic articles.					
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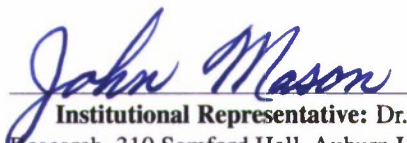
Final Report
Submitted to the Office of Naval Research

**Dynamic Resource Allocation to Improve
Service Performance in Order Fulfillment
Systems**

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ORDER RELEASE STRATEGIES FOR ORDER FULFILLMENT SYSTEMS WITH DEADLINES

1 Introduction

The role of the distribution center has changed dramatically in the past 30 years. Once the repositories of “stock” and “safety stock,” distribution centers are now a vital part of the business strategies of some of the world’s newest and most successful companies (e.g., Amazon, Zappos, Wal-Mart). Two major developments have led to this change in the U.S. First, manufacturing has continued to move overseas, from which goods now must be imported and distributed through distribution centers (DCs). That is, DCs have become a sort of “factory of the service economy.” Second, the rise of the internet and direct-to-consumer distribution has placed DCs at the very heart of what customers perceive as good service. If we get our products when the website tells us we will, we are happy customers.

Distribution centers in the Department of Defense have also become critical components in getting supplies to the warfighter. Recent emphasis on reducing overall inventory levels in DoD has heightened the need for DCs to be more responsive than in the past. If items are located in more remote locations — as will generally be the case when consolidating inventories — the ability to move them quickly is crucial.

But what does it mean, exactly, to “move items more quickly?” Does it really matter, for example, if flow time through a warehouse is eight hours instead of six? On a journey of 800 miles of transportation, what difference can two hours make? Answer: it depends on when those extra two hours occurred. If they include the last scheduled departure of the FedEx truck, then the customer’s wait time is extended not by two hours, but by 24 hours. Which is to say, those two hours (or 20 minutes, for that matter) can, *on the margin*, turn into an entire day.

This concept, that 20 minutes can turn into 24 hours of delay, is the result of fundamental differences between warehouse operations and transportation operations. Warehouses “produce” orders in a continuous stream; as evidenced by the stream of completed orders appearing on a shipping dock. Transportation processes, by contrast, are cyclical; to reach the economies of scale required to justify tractor-trailer trips, shipments are batched into larger loads and transported in daily cycles (e.g., the famous “evening sort” at FedEx and UPS hubs). Be-

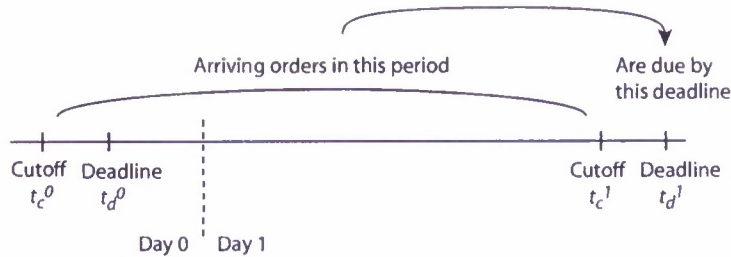


Figure 1: The Next Scheduled Deadline metric.

cause the continuous process of the warehouse's order fulfillment system meets the cyclical process of transportation, traditional performance metrics for continuous production processes such as flow time may not be appropriate (Doerr and Gue, 2011). We are back to the earlier question: Does the flow time of an order matter? The answer for most order fulfillment systems, we contend, is "not directly." More important is whether or not the order made it onto the next available truck.

2 Overview of the Research

This project has explored the implications of deadline-based metrics on order fulfillment operations. Our first contribution was to define a performance metric called *Next Scheduled Deadline*, or NSD (Doerr and Gue, 2011), which measures the fraction of orders each day arriving during a specified 24-hour period that are processed before a specific truck departure (see Figure 1). For example, if the cut-off time is 1300, and 1,000 orders arrive between 1300 on Day 1 and 1300 on Day 2, NSD is 90 percent if only 900 of those orders make it on the departing truck at 1700 on Day 2. This metric is currently in use at depots of the Defense Distribution Center (DDC) of Defense Logistics Agency (DLA).

The point of the metric is to motivate warehouse workers both to work harder near the deadline and to change internal processes in order to get more orders on the truck near the deadline. Doerr and Gue (2011) showed that in the presence of a properly set cut-off time and NSD goal, a simple model of motivated workers yields improved performance on NSD. Gue and Kim (2008a) developed steady-state sojourn time distribution models for orders arriving to a multi-stage, multi-server queueing system, which is a reasonable model of pick, pack and ship order fulfillment systems. They showed how to use the sojourn time distribution model

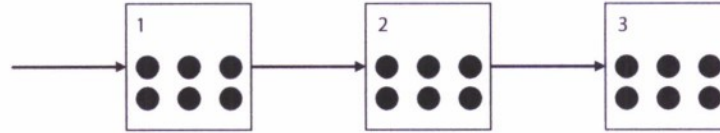


Figure 2: A small order fulfillment system modeled as a multi-stage, multi-server queue. Workstations correspond to the picking, packing, and shipping operations.

to set the cut-off time to achieve a target level of NSD.

We have also investigated questions of dynamic worker allocation in order to improve performance on NSD. The idea behind dynamic worker allocation is, just before the last truck departure, to move some workers from picking to shipping in an effort to flush the system of orders that otherwise would not make the truck. By doing so, however, picking capacity is depleted for a time, and this has implications for the next day's operations. The major research questions were,

1. Can an order fulfillment system be gamed in this way? That is, can workers be moved from picking to shipping to reduce NSD, or do the negative effects on the next day's operations mitigate (or worse) the benefit?
2. If NSD can be reduced by shifting workers from picking to shipping, how many workers should be moved, and when? How often should they be moved?
3. Under what conditions are these strategies most likely to yield benefit to the operation?

The results of our work are described in detail in Kim (2009), Gue and Kim (2008a), and Gue and Kim (2008b). Following is a summary.

We begin with a simple pick, pack and ship representation of order fulfillment that leads readily to a multi-stage, multi-server queueing model (Figure 2). Early testing of naïve worker allocation policies, such as “move n workers from picking to shipping t hours before the deadline,” suggested that a successful policy must be state-sensitive; that is, that it must consider how many orders are in queue in each part of the system and move workers only when there is profitable work to be done in a downstream operation. To decide if a move was “profitable,” we needed to know if the order to be worked had a reasonable chance of making it on the next departing truck. This idea gives rise to the need for a state-dependent sojourn time

distribution, with which we can compute the probability that a specific order will make it through the system in time for the next departure. Given that probability, we devise different rules for determining how many workers to move, and when.

Our method for building these state-dependent sojourn time distributions, which we describe in Gue and Kim (2008b), uses phase-type distributions and a novel Markov process representation of remaining time in service. It admits general interarrival and processing times in multi-stage, multi-server queueing systems, including non-cyclical networks. We can use this model to answer operational questions such as, "Given that an order is 7th in queue in a multi-server system, what is the probability it will complete service in the next 30 minutes?" Whitt (1999) developed for similar questions an approximation model based on the Normal distribution, but his methods (by his own admission) work well only when the number of servers is much greater than the length of the queue. By contrast, our methods work well under more general conditions (although we are unable to solve problems as large as those addressed by Whitt).

An extension of the single-stage model allows us to ask questions of orders in multi-stage, multi-server systems: "Given that an order is 7th in queue in stage 2, and that there are 4 orders in queue at stage 3, what is the probability it will complete service in the next 45 minutes?" We believe ours is the first work that allows analytical solutions to such questions.

The ability to estimate the probability that an order will complete service before a certain time allows us, in a standard order fulfillment system, to predict its "probability of success," and therefore to build dynamic worker allocation policies based on the state of the system. A simple state-dependent policy is the *flushing policy* (Kim, 2009, describes several more policies). The idea is to determine a particular time before the deadline each day to check the probability of success of the last order in the shipping queue. If that probability is below a threshold, move sufficient workers from picking to shipping raise its probability of success above the threshold (Figure 3). The outcome of such a policy is that, on some days, no workers move, but on others (when the shipping queue is large), several workers move to "flush" the system just before the truck leaves. Kim reports that such a policy can increase NSD by as much as 10 percent in some cases. In other words, using a dynamic worker allocation policy would allow 10 percent of customers to receive their shipments an entire day earlier than they otherwise would.

Finally, it is important to note that the flushing policy is unaffected by non-stationary arrival distributions, which was a deficiency of earlier work. Because the decision rule is state-based and dynamic, changing arrival patterns are dealt with as a matter of course.

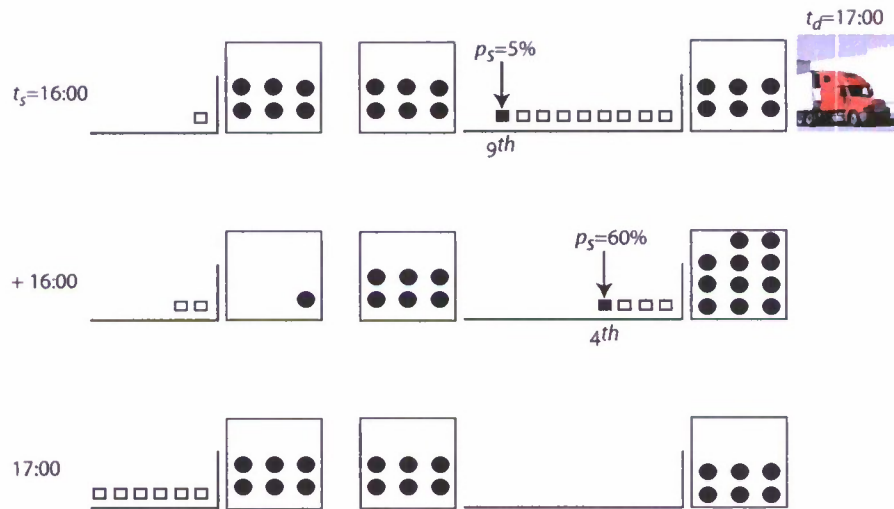


Figure 3: The flushing policy, which moves workers to shipping just before the deadline.

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The following approved information is submitted for the closing of the subject contract/grant on behalf of Dr. Kevin Gue in the Department of Industrial and Systems Engineering:

X **Final report or (Copy of transmittal letter) w/SF298**

_____ New Technology Summary Report (NASA NTSR)

_____ Final Invention Statement and Certification

_____ DD Form 882/MSFC Form 4204

If you need any additional information, please give me a call at (334) 844-2297.

Joanne Tolbert
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c: Dr. Kevin Gue